PROPERTIES OF MINOR IONS IN THE SOLAR WIND AND IMPLICATIONS FOR THE BACKGROUND SOLAR WIND PLASMA

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Final Report

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1.1 Scope of the Investigation

Ion charge states measured in situ in interplanetary space carry information on the properties of the solar wind plasma in the inner corona where these ion charge states are formed. The goal of the proposed research was to determine solar wind models and coronal observations that are necessary tools for the interpretation of the ion charge state observations made in situ in the solar wind.

1.2 Progress Made During Period 03/01 98 to 02/28 01

After the recent progress made in determning coronal plasma properties such as electron temperatures measured with the SUMER instrument on SOHO and ion flow speeds measured with UVCS on SOHO, we focused our study on the effect of non-Maxwellian electron distribution functions and differential ion outflow speeds on the formation of the ion charge states.

The SUMER observations show, in agreement with earlier observations and model studies, that the electron temperatures in the coronal dark lines which are the sources of the high speed solar wind, never exceed 10^6 K. Relative to these low coronal hole electron temperatures, the in situ ion charge states show systematic shifts to higher ionization states for all elements. Such a large, systematic shift cannot be attributed to uncertainties in observations and/or atomic data. It was shown by Esser and Edgar (2000 and 2001a) that the low coronal electron temperatures and high ion charge states can be reconciled if the coronal electron distribution function starts to develop a significant suprathermal halo already below 3 R_S. The ion fractions shown in Figure 1 result when the core electron temperature and the electron density profile as well as ion flow speeds are choosen in agreement with obeservations, and it is assumed that the shape of the coronal electron distribution function is similar to the one seen in situ in the solar wind.

Another possibility to produce the observed fractions are through significant differential flow speeds of ions of the same element. In all previous studies of solar wind ion fractions the possibility of differential flow speeds between ions of the same element has never been addressed. The only exception so far is a study of solar wind expansion which included O^{+5} and O^{+6} ions (Esser and Leer 1990). This study showed that for the low coronal densities which are found in coronal holes, ionization and recombination processes are not necessarily fast enough to couple ions of the same element sufficiently, and differential flow speeds of factors of 2 to 3 might exist close to the coronal base. In a study by Esser and Edgar (2001b) it was shown that if differential ion flow speeds are of order 100, then the in situ ion fractions would be formed even for low electron temperaturs and Maxwellian distributions. However, these differential flow speeds were shown to be much larger than what can be expected from theoretical considerations. The conclusion reached in this study so far is that differential ion flow speeds can modify the formation of ion fractions, but are not alone capable of

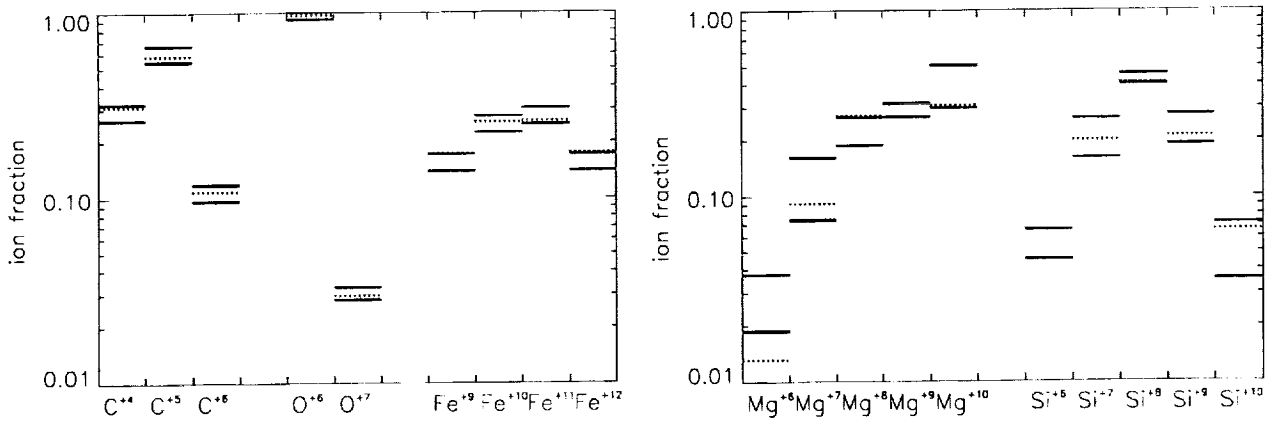

Figure 1: Limits on the ion fractions observed by SWICS/Ulysses (solid lines) and calculated fractions (dashed lines) if it is assumed that the halo on the electron distribution function is fully developed already in the inner corona (see Esser and Edgar 2001a).

producing high ionization states that agree with the observations. Additional energetization is needed, most likely in the form of non-Maxwellian electron distributions. Figure 2 shows the ion fraction distribution that results if electron temperature and density are chosen in agreement with observations, the electrons are Maxwellian and significant differential flow speeds exist between ions of the same element (see Esser and Edgar 2001b).

In addition to the above minor ion studies we have also carried out theoretical studies of minor ion expansion (e.g. Hu, Esser and Habbal 1999), of coronal plasma parameters important to the ion formation (e.g. Esser and Sasselov 1999), and observations of ion properties such as the Mg X effective temperature (Figure 3) (e.g. Esser et al. 1999 and Kohl et al. 1999).

The above studies of solar wind properties and non-equilibrium ion formation were used to investigate the accuracy of common spectral line diagnostic that is applied to determine first ionization potential effects. The non-equilibrium ionization effects on the ratio of Ne^{+5}/Mg^{+5} was studied in some detail (Edgar and Esser 2000). It was shown that non-equilibrium effects, as well as temperature and density effects, must be evalutaed in each case before conclusions on the FIP effect can be drawn from such spectral line diagnostic (Figure 4).

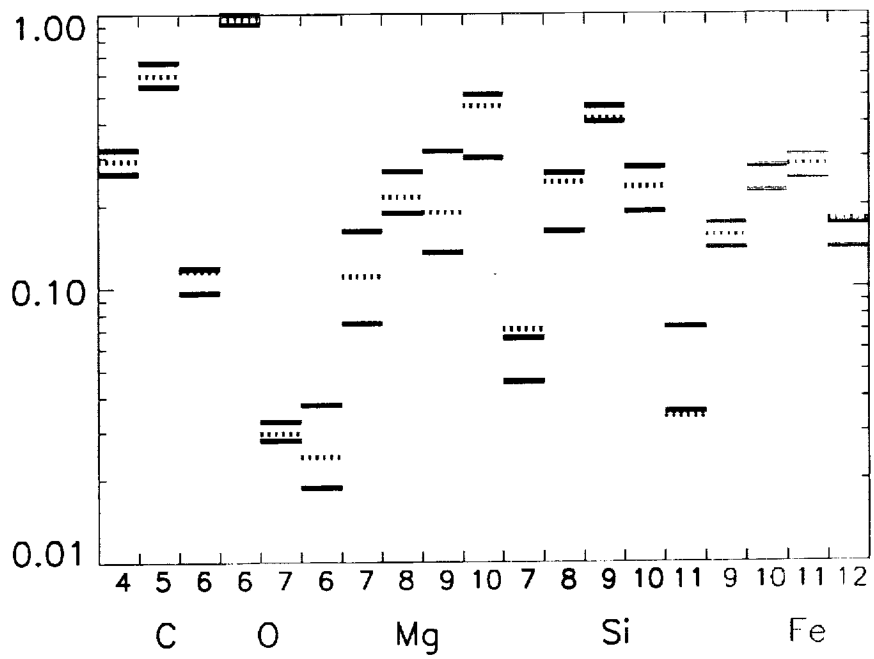

Figure 2: Limits on the ion fractions observed by SWICS/Ulysses (solid lines) and calculated fractions (dashed lines) if large differential flow speeds are assumed between ions of the same element (see Esser and Edgar 2001a).

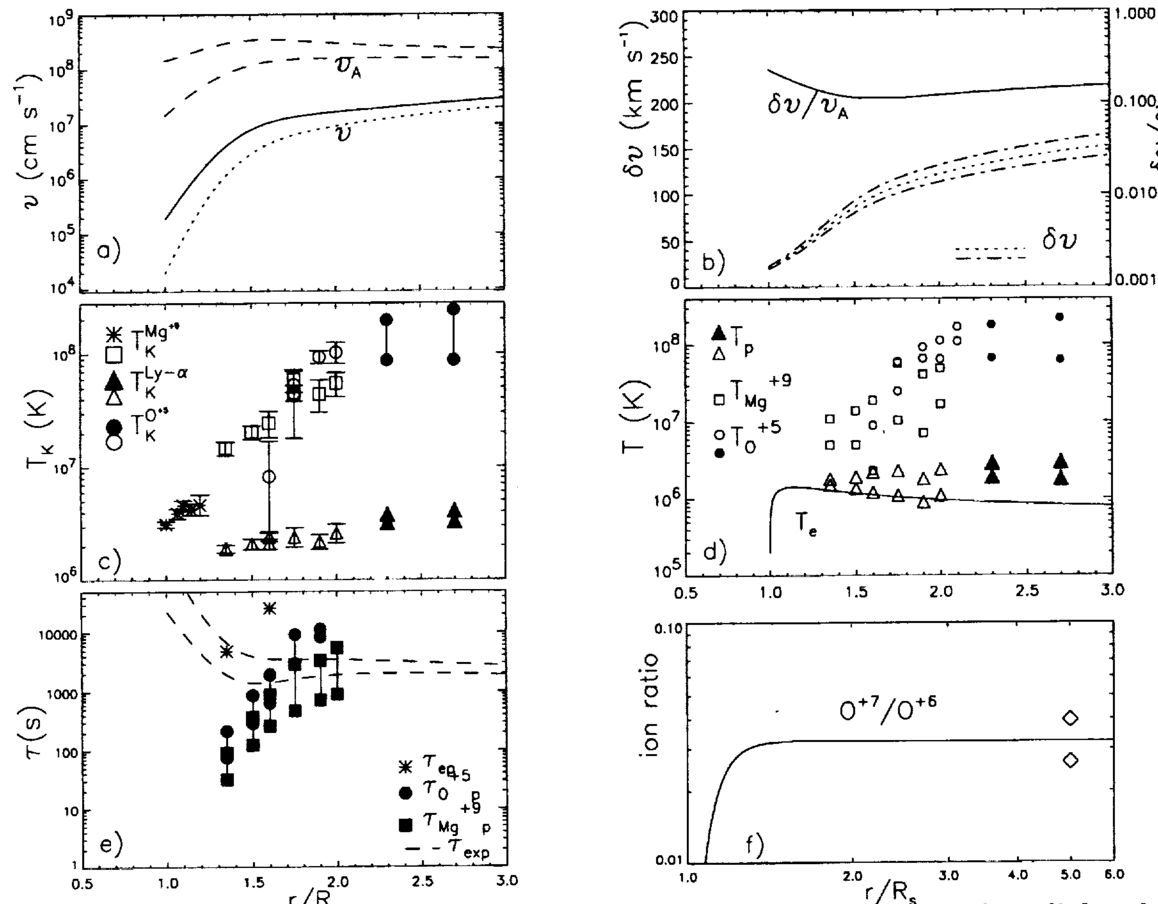

Figure 3: Plasma parameters derived from UVCS/SOHO and Spartan white light observations. These plasma parameters are used as constraints in the model calculations (from Esser et al. 1999).

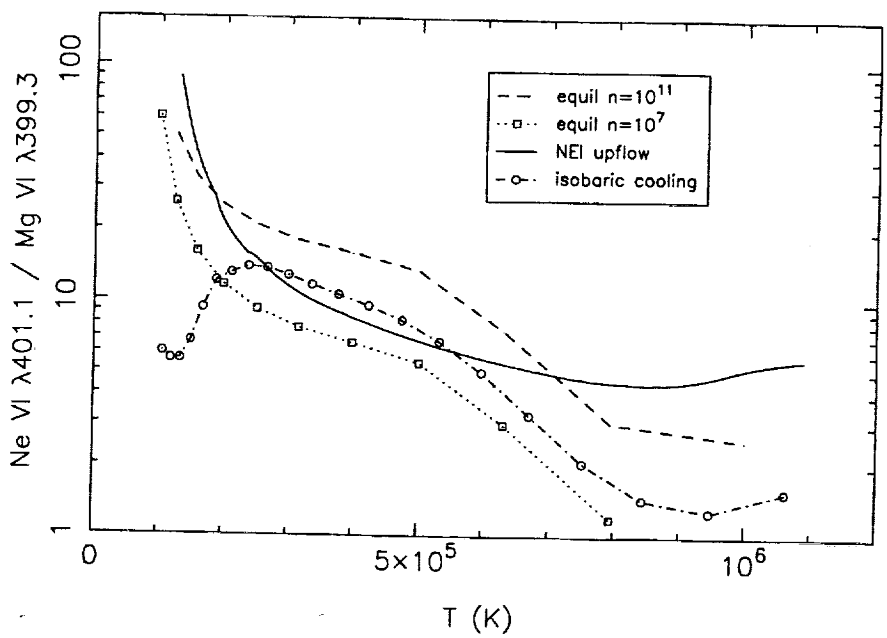

Figure 4: Ratio of Ne VI λ401.1/Mg VI λ399.3 of line emissivities for coronal equilibrium at two densities, for an isobaric cooling case, and for a typical solar wind outflow (from Edgar and Esser 2000). The region of weak temperature dependence has more or less disappeared in these cases, and the examples show that temperature, density and non-equilibrium effects are all important in the line ratio diagnostics.

2. Publications in Refereed Journals and Proceedings Fully or Partially Funded by the Grant

1. Y. Yamauchi, T. Tokumaru, M. Kojima, P. K. Manoharan, and R. Esser,Study of density fluctuations in the solar wind acceleration region, *J. Geophys. Res.*, **103**, 6571, 1998.

2. X. Li, S. R. Habbal, J. V. Hollweg, and R. Esser, Heating and cooling of protons by turbulence-driven ion cyclotron waves in the fast solar wind, *J. Geophys. Res.*, **104**, 2521, 1999.

3. R. Esser and D. Sasselov, On the discrepancy between atmospheric and coronal densities, *Astrophys. J. Lett.*, **521**, Aug. 20, 1999.

4. R. Esser, Coronal hole boundaries and interactions with adjacent regions, *Space Sci. Rev.*, **87**, 93, 1999.

5. J. L. Kohl, S. Fineschi, R. Esser, A. Ciaravella, S. R. Cranmer, L. D. Gardner, R. Suleiman, G. Noci and A. Modigliani, UVCS/SOHO observations of spectral line profiles in polar coronal holes, *Space Sci. Rev*, **87**, 233, 1999.

6. R. Esser, S. Fineschi, D. Dobrzycka, S. R. Habbal, R. J. Edgar, J. C. Raymond, J. L. Kohl, and M. Guhathakurta, Plasma properties in coronal holes derived from measurements of minor ion spectral lines and polarized white lightintensity, *Astrophys. J. Lett.*, **510**, L63, 1999.

7. J. L. Kohl, R. Esser, S. R. Cranmer, S. Fineschi, L. D. Gardner, A. V. Panasyuk, L. Strachan, R. M. Suleiman, R. A. Frazin, and G. Noci, EUV spectral line profiles in polar coronal holes from 1.3 to 3.0 R_S, *Astrophys. J. Lett.*, **510**, L59, 1999.

8. R. Esser, Solar Wind Acceleration, Encyclopedia of Astronomy and Astrophysics, ed. E. Priest, 2000.

9. Y.-Q. Hu, R. Esser, and S. R. Habbal, A Four-Fluid turbulence-driven solar wind model for preferential acceleration and heating of heavy ions, *J. Geophys. Res.*, **105**, 5093, 2000.

10. E. Kaghashvili and R. Esser, Velocity shear induced mode-conversion in the solar wind and streamer plasma, *Astrophys. J.*, **539**, 463, 2000.

11. R. Esser and R. Edgar, Reconciling spectroscopic electron temperature measurements in the solar corona with in situ charge state observations, *Astrophys. J. Lett.*, **532**, L71, 2000.

12. R. Edgar and R. Esser, Nonequilibrium ionization and first ionization potential effect diagnostic, *Astrophys. J. Lett.*, **538**, L167, 2000.

13. R. Esser and R. Edgar, Constraints on ion outflow speeds and electron distribution function in the corona from SUMER electron temperatures and SWICS ion fractions, in press, *Adv. Space Res.*, 2001a.

14. R. Esser and R. Edgar, Differential flow speeds of ions of the same element: Effects on solar wind ionization fractions, in press, *Astrophys. J.* 2001b.

3. Invited Presentations at Meetings

R. Esser, Working Group 3 report: Coronal hole boundaries and interactions with adjacent regions, SOHO7, Ann Harbor, Maine, USA, 1998.

R. Esser, An update on understanding the corona, IAGA division IV reporter reviews, IAGA meeting, Birmingham, England, 1999.

S. R. Cranmer and R. Esser, Cyclotron resonance of ions in the solar corona: Observations and models, presented by R. Esser at IAGA meeting, Hanoi, Vietnam, 2001.